

**2013 Annual Report for ONR Sponsored Research:  
A Multiscale Study of Tropical Cyclone Formation,  
Structure Change and Predictability in the Western North  
Pacific Region & TCS08 Experiment Support**

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## **LONG-TERM GOALS AND OBJECTIVES**

The overarching objectives of this research project are to obtain an improved understanding of the formation, intensification, predictability and structure change of tropical cyclones in the Western Pacific region. These new insights will ultimately improve forecast guidance for U.S. Naval operations in this region. In this year's report I will focus on one of our main findings regarding Nuri's genesis dynamics on the mesoscale.

## **APPROACH**

As part of the PI's published research findings obtained during prior TCS08 work, his team wrote two peer-reviewed manuscripts detailing the synoptic and meso-alpha scale flow characteristics and thermodynamic characteristics of Nuri's genesis (Montgomery et al. 2010, Montgomery and Smith 2012). This work is complemented by that of David Raymond and group who have analyzed the mesoscale vorticity budget of Nuri's formation and who have presented a 'thermodynamic control' hypothesis as a necessary condition for Nuri's formation. As a result of these complementary investigations, new and important questions have arisen about the dynamical and thermodynamical mechanisms of Nuri's observed genesis and the genesis of tropical cyclones more generally. For example, the research of the Raymond group (Raymond and Lopez 2011, hereafter RL11; Raymond et al. 2011; hereafter Retal11) has suggested that the pre-Nuri disturbance was spinning down on the first day of TCS08 observations (Nuri 1) and it was not until a thermodynamic stabilization occurred in the lower troposphere on the second day of research flight observations (Nuri 2) that allowed the pre-Nuri disturbance to intensify into a tropical depression and later a tropical storm. In recent work of Montgomery and Smith (2012) and Smith and Montgomery (2012) a number of scientific questions were raised about the thermodynamic arguments put forth by Raymond and colleagues. Given the uniqueness of the TCS08 data collected, and the related implications of the ongoing scientific debate, we think it is important to carry out an independent analysis of the dropwindsonde and Doppler radar data collected during the Nuri's formation and test the conclusions of Raymond and colleagues.

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## CURRENT WORK

Given the scientific importance of the issues summarized above, this year's ONR work has focused on answering the following three questions regarding the observed formation of typhoon Nuri:

- Was there spin-down on the system-scale in the lower-levels of the developing Typhoon Nuri disturbance between Nuri 1 and Nuri 2 as suggested by RL11?
- Is the thermodynamic control hypothesis put forth by RL11 and Retall1 a necessary condition for tropical cyclogenesis in the case of Typhoon Nuri?
- How does the chosen horizontal area of integration for the corresponding circulation budget calculations affect the results and scientific conclusions drawn from these analyses?

Due to space restrictions, other related research supported by this grant is listed in the Publication List of this report and is available via the PI's website listed above.

## WORK COMPLETED

Aircraft reconnaissance data collected during the TCS08 field campaign have been used to answer the three questions raised above. The results of this work are detailed in the manuscript by Lussier *et al.* (2013).

### Mesoscale vorticity and circulation dynamics

The vorticity dynamics of Nuri's genesis were diagnosed using the 10 km SAMURAI analyses described in the PI's prior annual report. The SAMURAI methodology is complementary to and independent of the objective analysis methodology developed by RL11. Details of SAMURAI that are pertinent to the mesoscale analysis conducted for Nuri's genesis are described in Lussier *et al.* (2013).

Following Haynes and McIntyre (1987) and RL11, the vertical vorticity equation may be rewritten into flux form as follows:

$$\frac{\partial \eta}{\partial t} = -\mathbf{V}_h \cdot \nabla \mathbf{Z} + \hat{\mathbf{k}} \cdot \nabla \theta \times \mathbf{V}_h \quad (1)$$

where  $\eta$  is the absolute vertical vorticity, the subscript  $h$  represents the horizontal vector quantity,  $\theta$  is potential temperature. The Exner function is defined as:  $\Pi = \left(\frac{p}{p_0}\right)^{R_d/c_p}$ , where  $p$  is the pressure,  $p_0$  is the pressure at a reference level (typically 1000 hPa),  $R_d$  is the gas constant for dry air, and  $c_p$  is the heat capacity of dry air at constant pressure. The vector vorticity flux,  $\mathbf{Z}$ , is defined as follows:

$$\mathbf{Z} = Z_1 + Z_2 + Z_3 = \eta_z \mathbf{v}_h - \eta_h v_z + \mathbf{k} \times \mathbf{F} \quad (2)$$

where the  $z$ -subscript represents the vertical component of the corresponding vector quantity,  $\eta_h$  denotes the horizontal vorticity vector, and  $\mathbf{F}$  represents the non-conservative vector force per unit mass associated with the divergence of Reynolds stresses. If we assume that  $\mathbf{F}$  can be approximated

by horizontal friction only, then it can be parameterized in a simple and plausible way (following RL11) as follows:

$$\mathbf{F} = \frac{\tau}{\rho} \exp(-z/z_s)/z_s \quad (3)$$

where  $\rho$  is air density,  $z$  is height,  $z_s$  is a characteristic boundary layer height (1.25 km) and the surface stress  $\tau$  is defined as:

$$\tau = -\rho_{BL} C_D |U_{BL}| \mathbf{U}_{BL} \quad (4)$$

where the subscript  $BL$  represents conditions in the boundary layer,  $U$  is the horizontal wind and  $C_D$  is the surface drag coefficient, defined in this analysis as:

$$C_D = (1 + 0.028 |U_{BL}|) \times 10^{-3} \quad (5)$$

Now, integrating Equation (1) over a horizontal surface, and neglecting the small contribution from the baroclinic vorticity generation term, results in the circulation tendency equation:

$$\frac{d\Gamma_a}{dt} = \int_A \nabla \cdot \mathbf{Z} dA \quad (6)$$

where  $\Gamma_a$  is the absolute circulation and  $A$  is the area over which the integration is performed (in this work, a square box). By applying Gauss's divergence theorem, the circulation tendency can also be calculated using the line integral form:

$$\frac{d\Gamma_a}{dt} = -\oint \mathbf{v}_n \eta_z dl + \oint \eta_n \mathbf{v}_z dl + \oint F_t dl \quad (7)$$

where  $dl$  is the positive line element along the perimeter of the integration area, the subscript  $n$  denotes the outward normal component of the variable along the circuit, and the subscript  $t$  denotes the tangential component of the variable in the sense of the circuit. The integration is taken in a counter-clockwise sense in accordance with the right-hand-rule. Equation (7) shows that changes to the absolute circulation occur through: i) convergence of absolute vorticity (first term); ii) vortex tilting-like term (second term); and iii) the frictional spin down tendency (third term). RL11 argue that the spin-up of a vortex in the lower levels can occur only if the spin-up from convergence of absolute vorticity exceeds the frictional spin-down tendency. Davis and Galarneau (2011) show that the convergence term can be broken down into 'mean' and 'eddy' contributions along the circuit:

$$-\oint \mathbf{v}_n \eta_z dl = -\bar{\eta} \tilde{\delta} A - \oint \eta' \mathbf{v}' \cdot \hat{\mathbf{n}} dl \quad (8)$$

where  $\delta$  is the horizontal divergence, the overbars represent the mean over the perimeter of the circuit, the primes indicate perturbations from this mean, the tildes indicate an areal average over the circuit, and  $\mathbf{v}$  is shorthand for the horizontal velocity vector. The first term on the RHS of Equation (8) represents vortex-tube stretching averaged over the area contained within the circuit, while the second term in this equation represents the change in the absolute circulation owed to horizontal eddy fluxes of vertical vorticity into and out of the integration area.

## RESULTS

As described above, one of the objectives of this year's work was to quantify how the circulation dynamics vary at different locations within Nuri's wave pouch. With this objective in mind, the SAMURAI analyses were used to calculate terms from the circulation tendency equation (Eq. 7) and other variable properties in 0.2 degree length boxes, centered on the 1.5 km altitude sweet spot position. We choose the 1.5 km altitude sweet spot position for these calculations because the maximum amplitude of the pre-Nuri wave was in the lower troposphere (Montgomery *et al.*, 2010a)<sup>1</sup>. The advantages of this analysis methodology are: i) It is a systematic way to analyze the kinematics and dynamics at varying distances from the sweet spot position; ii) It allows for a straightforward comparison of the various spin-up contributions between research flights; iii) The methodology is optimally suited to observe and quantify the development that ensues around the sweet spot, the so-called 'attractor point' predicted by the new cyclogenesis model (Montgomery *et al.* 2012; Montgomery *et al.* 2010b, Dunkerton *et al.* 2009); and iv) Anchoring the analysis to the moving sweet spot of the parent disturbance provides useful information on the vertical alignment of the vortex and depth of the wave pouch. The second and third points are especially important as there is considerable variability in the areal coverage of the aircraft data during the Nuri missions (see Figure 1).

### A. Analyzed circulation tendency

Figure 2 shows the analyzed circulation tendency (Eq. 7) for Nuri 1 using the 10 km SAMURAI analysis. The circulation calculations are conducted using square boxes of progressively increasing size in 0.2 degree length increments centered on the 850 hPa sweet spot position. The top row of Figure 2 shows the *net tendency* of the absolute circulation during Nuri 1 over the analyzed area in a distance/height format. The next three rows show the individual terms comprising the circulation tendency equation (Eq. 7) in the same distance/height format. The results indicate i) Low-level (0 to 4 km altitude) spin-up tendency out to 0.8 degrees from the sweet spot. In this pouch-center region, the spin-up is a result of the influx of absolute cyclonic vorticity dominating frictional spin down. ii) Mid-tropospheric (4 – 7 km altitude) spin-down tendency from the sweet spot to an approximately two degree box size. (While the vortex misalignment plays a small role in creating this area of mid-level spin-down tendency, the major contributing factor is the negative convergence tendency at mid-levels.) iii) Barring a shallow region (< 1 km depth) near the surface for box sizes between 2 and 2.7 degrees, there is a clear spin up tendency throughout the observed troposphere for boxes greater than 2 degree lengths. iv) Maximum frictional spin down tendency occurs in the boundary layer beyond 2.25 degree box lengths. v) An area of low-level spin-down tendency located within the 1-2 degree boxes from the sweet spot connecting to the aforementioned surface-based spin-down tendency. (The surface-based spin-down found for the 2-2.7 degree box lengths is primarily caused by frictional spin-down exceeding the influx of absolute vorticity. However, the region of spin-down above the boundary layer between the 1-2 degree box lengths is a combination of friction, negative eddy fluxes (not shown), and negative contributions from the tilting term.) In summary: The foregoing analysis suggests that there is a combination of low-level spin-up and spin-down within the wave pouch. ***Nevertheless, on the whole the data indicate that the pre-Nuri disturbance during Nuri 1 is not spinning down, but spinning up in the low-levels.***

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<sup>1</sup> The choice of 1.5 km altitude is consistent with the observed properties of easterly waves in the western North Pacific basin dating back to the 1970's, which found that the maximum amplitude of easterly waves was in the lower troposphere, at or below 850 hPa (Reed and Recker, 1971; Chang, 1970).

## B. System-scale view of Nuri's genesis

A complementary way to investigate whether the system-scale circulation is spinning up may be obtained by examining the time evolution of azimuthally-averaged absolute angular momentum surfaces between Nuri 1 and Nuri 2 (e.g., Montgomery and Smith 2013, their figure 13). The azimuthally-averaged absolute angular momentum is defined by  $M = rv + fr^2/2$ , where  $r$  is the radius from the sweet spot position,  $v$  is the azimuthally-averaged, storm-relative tangential velocity, and  $f$  is the Coriolis parameter at the reference latitude of the sweet spot at 1.5 km altitude. Above the frictional boundary layer,  $M$  is approximately materially conserved. Therefore as rings of fluid are drawn inwards the tangential wind increases. Figure 3(a, b) shows radius-height cross sections of azimuthally-averaged tangential wind (top, shaded) and absolute angular momentum (top, contours) for the Nuri 1 (a) and Nuri 2 (b) flights, respectively. Figure 3 (c, bottom) shows the difference in azimuthally-averaged tangential wind between Nuri 2 and Nuri 1.

The tangential velocity isopleths in Figure 3 show that in the case of Nuri 1, the maximum tangential wind resides in the lower-levels and is located near the outermost ranges of the analysis domain. For Nuri 2, the maximum low-level tangential wind has moved inwards, closer to the sweet spot, and the magnitude of the tangential wind has correspondingly increased in the lower and middle-troposphere. The increase of tangential wind in the mid-troposphere is consistent also with an improved vertical alignment of the vortex as discussed further in Lussier *et al.* (2013) and suggests a deepening wave pouch.

The M-surfaces in Figure 3 show higher values of  $M$  moving inwards between Nuri 1 and Nuri 2. The inward-moving  $M$  surfaces, in conjunction with its approximate material conservation above the boundary layer, imply an amplification of the pouch-relative tangential wind field. ***These characteristics are consistent with a system undergoing development between Nuri 1 and Nuri 2. These results support the circulation tendency results summarized above and affirm that, on the system-scale circulation, the pre-Nuri disturbance is undergoing spin up in the low-levels between Nuri 1 and Nuri 2.***

## IMPACTS

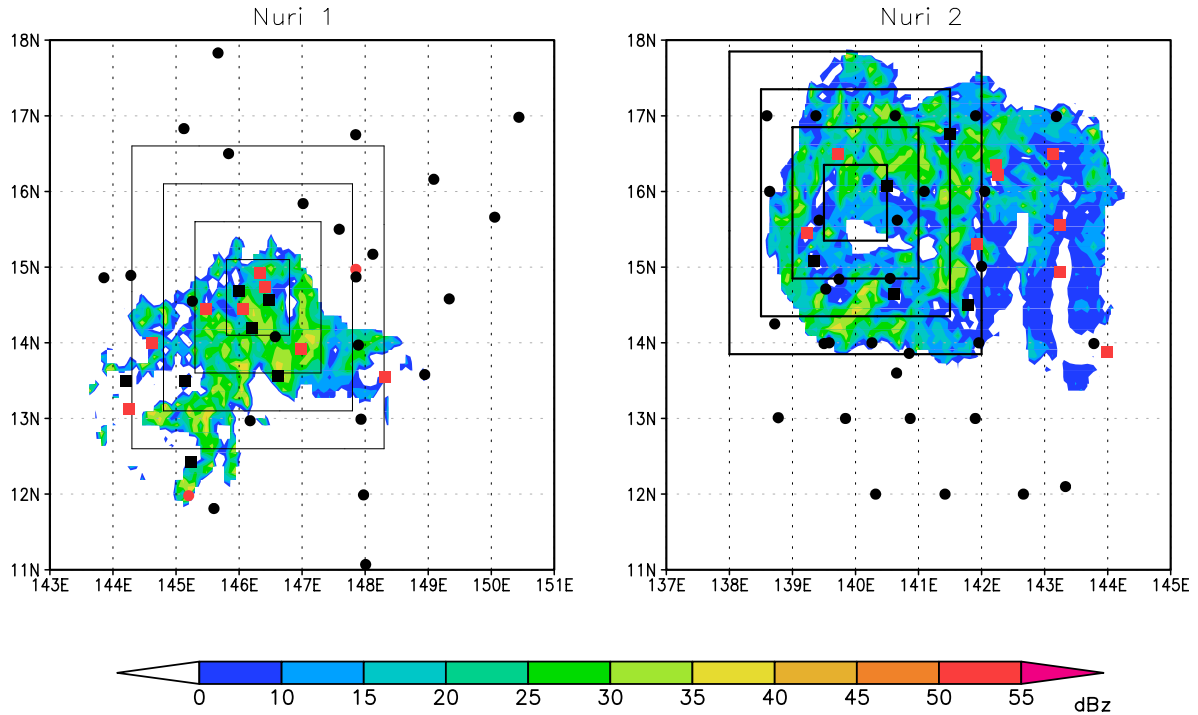
The analyses and interpretations presented herein have provided answers to the three questions posed at the beginning of this report. First, the magnitude of the low and mid-level circulation increased from Nuri 1 to Nuri 2. Second, the circulation tendency analysis indicates that the low-level tangential winds in the Nuri disturbance were amplifying from the beginning of the observation period both in the core and outer region of the pouch. Any thermal stabilization of the atmosphere that occurred during Nuri 2 (shown in Lussier *et al.*, *op. cit.*) appears incidental rather than essential to the storm development. Third, the distinct advantages of examining the dynamics of tropical cyclogenesis in a frame of reference anchored on the translating sweet spot position were demonstrated for these observational analyses.

The findings of this study are consistent in some respects to that of Raymond and colleagues, but differ in their suggested key result and related scientific implication that the pre-Nuri disturbance was spinning down on the first day of observations. The findings herein strongly support the marsupial model of Dunkerton *et al.* (2009), Montgomery *et al.* (2010b) and Montgomery *et al.* (2012) positing

that the Kelvin cat's eye circulation of the parent wave-like disturbance provides a favorable environment for intrinsic convective-vorticity organization and low-level spin-up on the mesoscale.

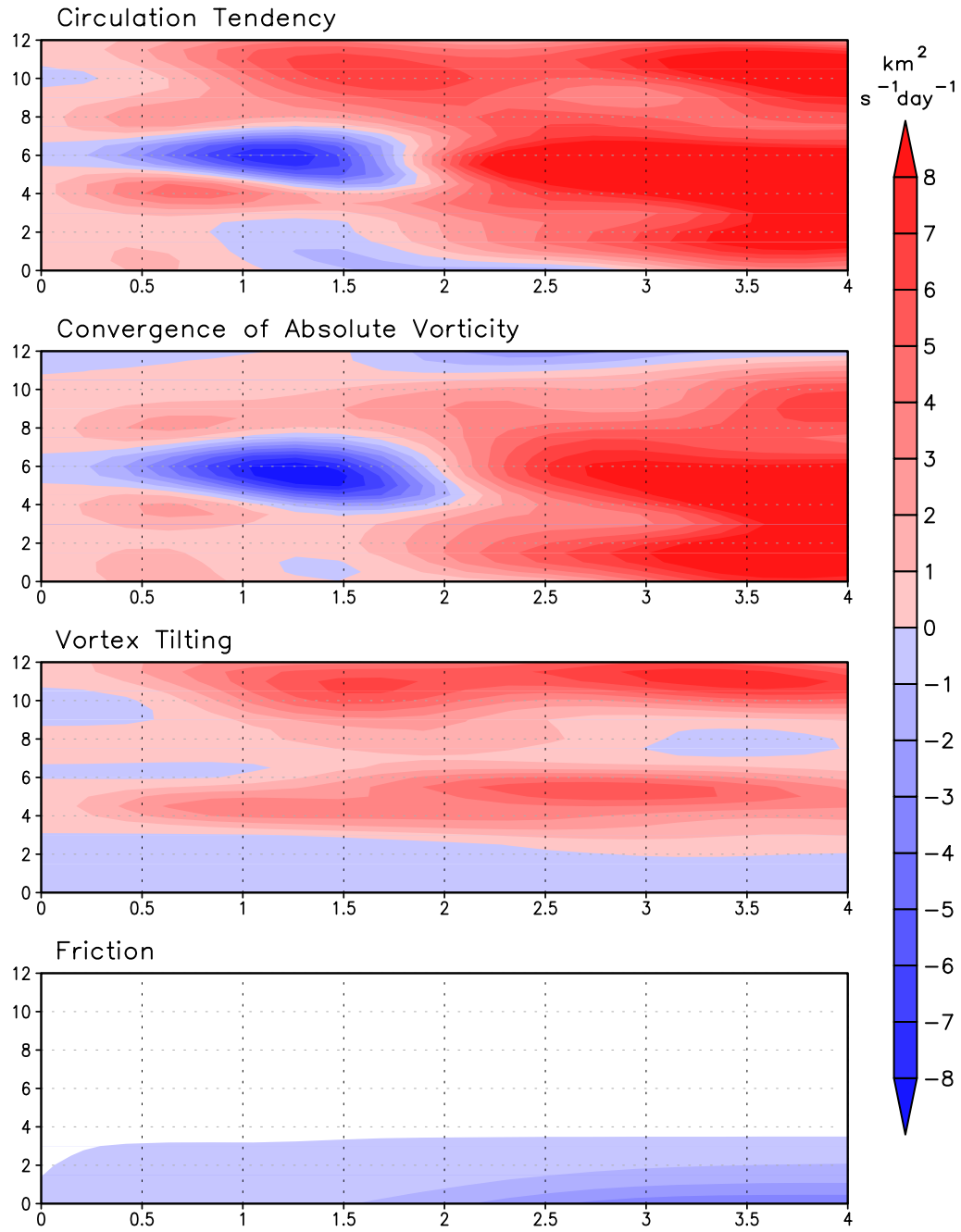
## RELATED PROJECTS

The TCS08 work summarized in this year's annual report is synergistic with the National Science Foundation experiment called Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT) conducted in Atlantic basin during the summer of 2010<sup>4</sup>.



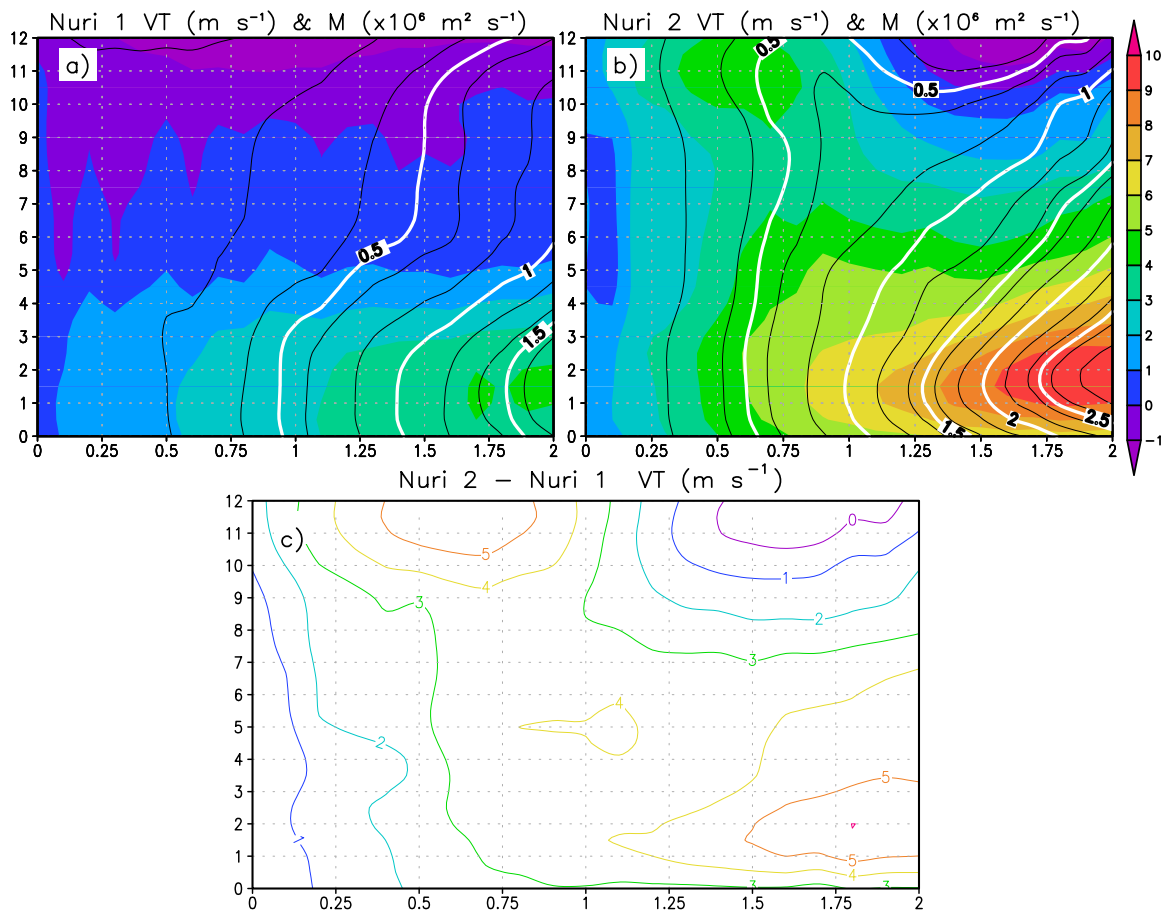
**Figure 1.** ELDORA radar reflectivity composite (in dBz) at 3 km altitude for Nuri 1 (left) and Nuri 2 (right) superimposed with dropwindsonde locations. The dropwindsondes from the USAF C130 (filled circles) and NRL P3 (filled squares) have been translated to their 00 UTC positions using a (westward) phase speed of  $-7 \text{ m s}^{-1}$ . The red circles and boxes indicate dropwindsondes with no retrieved wind data. The square boxes shown are at one-degree increments, increasing from one degree to four degrees, and represent the domain used in several of the analyses by Lussier *et al.* (2013). The boxes are centered on the sweet spot position at 1.5 km altitude within the pre-Nuri wave as derived from the SAMURAI analyses. The abscissa is longitude and the ordinate is latitude.

<sup>4</sup> The P.I. of this ONR grant was also the lead P.I. of the NSF-sponsored PREDICT experiment in 2010 (see Montgomery *et al.* 2012 for a summary of some first results from the PREDICT experiment).



**Figure 2. Four-panel height/distance cross-section of each term from the circulation tendency equation (Eq. 7) for Nuri 1. The abscissa is the length of the box (degrees) on which the integration is performed and is centered on the sweet spot position at 1.5 km altitude. The ordinate is height (km).**





**Figure 3.** Three-panel plot of tangential wind (top, shaded) and absolute angular momentum  $M$  (top, contours) for Nuri 1 (a) and Nuri 2 (b). The  $M$  surfaces are plotted at  $0.2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$  contours (white) and are highlighted (black) at  $0.5 \times 10^6 \text{ m}^2 \text{ s}^{-1}$  intervals. The difference in tangential wind speed between Nuri 2 and Nuri 1 is plotted in (c). The abscissa is radial distance (degrees) from the sweet spot position at 1.5 km altitude. The ordinate is height (km).

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## **PUBLICATIONS COMPLETED UNDER SUPPORT OF THIS RESEARCH GRANT**

**[32 total: 31 refereed and published or in press, 1 in review]**

- Abarca, S. F., and **M. T. Montgomery**, 2013: Essential dynamics of secondary eyewall formation. *J. Atmos. Sci.*, **70**, 3216-3230, [refereed, published].
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## **AWARDS RECEIVED DURING THIS GRANT PERIOD**

In December of 2013, the P.I. was awarded a medallion at the NPS Graduation Ceremony for the distinction of “Distinguished Professor of Meteorology.”

In January of 2012, the PI and his co-authors (Drs. Frank Marks, Bob Burpee and Peter Black) were awarded “best scientific paper award for 2010” from the National Oceanic and Atmospheric Administration. The published paper was entitled “**Structure of the Eye and Eyewall of Hurricane Hugo (1989)** and was published in *Mon. Wea. Rev.*, **136**, 1237-1259.